A reference model for presentation of studies in competency-based education in engineering and computing

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Abstract. *Competency-Based Education (CBE) has established itself as an effective educational method, as it focuses on the development of essential skills and competencies for professional practice. However, in the field of computing and engineering, this approach is still underrepresented. One of the challenges in the area is the lack of standardization in the way as studies are described and documented. This hinders the comprehension on the topic and the studies replication. This paper proposes a reference model supporting researchers on understanding and presentation of studies on CBE. The model was developed through an iterative and incremental process, following a rigorous selection of primary studies: each selected study incorporates new dimensions and attributes to the model. The proposed model has the potential to be supportive, as it can be used as a basis both for presenting studies on CBE and for analyzing the quality of published work.*

Resumo. *O Ensino Baseado em Competências (EBC) tem se consolidado como um método educacional eficaz, pois foca no desenvolvimento de habilidades e competências essenciais para a prática profissional. No entanto, no campo da computação e engenharias, essa abordagem ainda é pouco explorada. Um desafio que retarda o progresso nessas duas áreas é a falta de padronização na forma como os estudos são descritos e documentados. Essa inconsistência dificulta a compreensão geral da área e a replicação de estudos. Este trabalho propõe um modelo de referência com o objetivo de padronizar a apresentação de intervenções de EBC nas áreas de computação e engenharias. O modelo foi desenvolvido a partir de um processo iterativo e incremental, após uma rigorosa etapa de seleção de estudos primários: cada novo estudo selecionado incorpora novas dimensões e atributos sobre EBC. O modelo proposto tem o potencial de apoiar, pois pode ser utilizado como base tanto para apresentação de estudos sobre EBC, como para análise da qualidade de trabalhos publicados.*

1. Introduction

In recent decades, Competency-Based Education (CBE) has received increasing attention in higher education institutions. This method has being adopted with the aim of increasing the quality of the curriculum reinforcing that students are not limited to theory, but also developing the ability to apply knowledge in a practical way

[Fastré et al. 2014, Miranda et al. 2021, Wang et al. 2021, Brauer 2021]. Unlike traditional educational methods, CBE places emphasis on ensuring that students develop practical skills and attitudes specifically aimed at solving real-world problems in the workplace [Northrup 2016, Caeiro Rodriguez et al. 2021]. CBE can offer significant benefits, but the implementation of CBE still faces obstacles in many educational institutions, mainly because of the lack of resources and teaching materials exploring this methodology in technology and engineering courses.

While CBE has proven effective in areas such as healthcare, which require practical skills and precision, it faces significant challenges in fields such as computing and engineering. A literature review on the use of CBE in higher engineering education [Henri et al. 2017] revealed a low consensus on how to structure study programs and assess competencies. In addition, there are researches indicating that computer science educators face difficulties when classifying competency-based learning objectives [Masapanta-Carrión and Velázquez-Iturbide 2018, Gluga et al. 2012]. Another relevant factor is that competences in these technological domains require constant updating and specialized resources for assessment, as well as a focus on the practical application of skills in the work environment [Bowers and Sabin 2024].

Despite the growing interest of computer science educators in CBE [Cruz et al. 2023], there is still a significant challenge: the absence of a well-defined framework for organizing and presenting research in this area. This gap hinders the systematic understanding and wider implementation of CBE in higher education, especially in computing and engineering courses [Mihnev et al. 2021, Kiesler and Pfülb 2023].

Recent studies reinforce this need. For example, [Cruz et al. 2023] investigated the perception of higher education teachers about the adoption of CBE in computing, highlighting challenges related to its implementation and evaluation in the Brazilian context. [Raj et al. 2022] discuss the application of CBE in professional accreditation in computing, highlighting the importance of defining clear competences to guide academic and professional training.

In order to support and facilitate the construction of research on CBE, we have developed a model aimed at structuring work on this subject, especially in computing and engineering. The model covers a set of attributes and input examples for the presentation of research, allowing for greater clarity and systematicity in the formulation of studies. Its construction followed a rigorous protocol for selecting primary studies and was conducted iteratively: new attributes and examples were added progressively based on a detailed analysis of the existing literature.

This article describes the characteristics of the model and emphasizes its role in organizing and structuring tasks effectively. The 2 section provides basic information on the method for developing the model, while Section 3 explains the methodology. The results are analyzed in Section 4, the discussion of the work is in Section 5 and the contributions and conclusions are presented in Section 6.

2. Background

This section outlines the key concepts that underpin the theoretical framework used to contextualize the proposed model.

2.1. Competency-Based Education

A widely used definition of competence is an individual's degree of proficiency in applying knowledge, skills and dispositions to successfully perform specific tasks in a given context [Force 2020]. This approach is in line with the principles of CBE, which emerged in the United States around the 1960s, when institutions began to question the traditional model of teaching and analyze whether the knowledge acquired in the classroom could be effectively applied outside the school environment.

In recent years, CBE has received more attention. The underlying theory is that a greater proportion of undergraduate students can achieve proficiency in a specific area if they have the freedom to progress at their own pace and if learning experiences are tailored to their needs and interests [Lewis et al. 2014, Patrick and Sturgis 2013].

By linking learning to real work contexts, CBE trains professionals capable of tackling complex issues and making efficient decisions, as students learn through tasks and assessments that simulate the challenges of the job market [Raj et al. 2022].

In areas such as engineering and computing, where the integration of theory and practice is crucial to the performance of tasks, CBE stands out as an effective methodology compared to other pedagogical approaches [Dedović and Mušić 2017].

2.2. Related Work

Although still a little explored area, CBE in engineering and computing education has already generated some research, with several authors examining its benefits. As a result, the number of studies in this field is steadily increasing, paving the way for comprehensive overviews that explore various aspects of the application of CBE in higher computer science and engineering education.

[Zaitseva and Misnevs 2019]'s work describes the e-Competencies developed in the Software Engineering course and shows how these competencies were assessed. In this study, the Software Engineering course at two technical universities was analyzed to identify the competences it can provide. For this purpose, the European e-Competence Framework was used. As a result, 9 competences in different e-Competence areas were identified in the bachelor's program and 16 in the master's program.

[Kiesler and Pfülb 2023] highlight the challenges in defining and classifying the skills expected in introductory programming courses, proposing a model based on machine learning to assess the cognitive complexity of these skills. In a comparative study, [Kiesler and Thorbrügge 2022] analyze the competences required in higher education and vocational training, revealing similarities and gaps that impact the transition between the two educational systems and the validation of competences acquired in different contexts. [Frezza et al. 2018] present a model of competences for computing education, arguing that the combination of knowledge, skills and dispositions is essential to define a comprehensive framework that is adaptable to changes in the discipline. These studies reinforce the importance of modeling and structuring competencies in a systematic way, promoting more effective teaching aligned with the needs of contemporary computing.

In addition, several studies have explored ways of assessing competences in higher education, especially in computing and engineering. Research such as that by [Mäses et al. 2021, Félix-Herrán et al. 2019, Garay-Rondero et al. 2021,

Rincon-Flores et al. 2021] have been important for understanding and improving methods for assessing competences in these fields. These studies show that the field is advancing in both the implementation and assessment of competencies, using approaches such as practical activities, case studies and simulations.

The proposed model contributes significantly to the advancement of new work and implementation frameworks in the field of Competency-Based Education (CBE) for computing and engineering. By providing insights into competence assessment methods, it facilitates the development of practical approaches, supporting the design of curricula and methodologies aligned with market demands and the preparation of highly qualified professionals.

3. Methodology

This section details the steps followed to carry out this research. To build the model is essential to extract data from a set of relevant articles presenting studies focusing on CBE. Due to this, as the first stage, a protocol was drawn up for the selection of primary studies considered as input for the research. Defining the protocol is crucial to avoid the choice of studies being influenced by the researcher's expectations, thus reducing the risk of bias. In the second stage, the primary studies were read and the dimensions of the interventions on CBE were extracted supporting to build the framework proposed in this research.

3.1. First stage - identifying primary studies

This step follows the guideline proposed for the selection phase of the systematic review method drawn up by the authors of this article, which searches for works that address CBE in higher education in computing and engineering, this review is still in the publication phase. Systematic reviews provide overviews of the state of knowledge in a field, from which future research priorities can be identified [Page et al. 2021]. The selection phase of a systematic review involves defining a protocol for identifying relevant primary studies that address the topic under investigation. In this case, we consider studies that present some analysis, evaluation, implementation or development of methods that adopt CBE.

Two researchers work on that stage that we summarize as follows. The first step consider the identification of control group of papers identified in a non-systematic search. Five papers were considered as the control group, used for calibration of the researchers perception on the topic. The second step consider search string (defined in an iterative process) and searching. The final search string is *("competency-based education" OR "competence-based education" OR "competency-based learning" OR "competence-based learning") AND ("higher education" OR "higher learning") AND ("engineering" OR "computer science" OR "computing" OR "information technology" OR "engineering education" OR "engineering learning")*. The choice of the databases was based on other references and in the experience of the researchers. They were: ACM Digital Library, IEEE Xplore, Springer, Scopus, Science Direct and Taylor & Francis. Searches were limited to peer-reviewed journal articles published between January 2015 and August 2024.

For the third step, the two researchers worked independently, meeting for consensus. Each research read title and abstract of the 797 papers returned from the search string. After checking disagreement and meet for consensus, 79 papers were considered

for the next phase. This phase consists of the papers in-depth reading. The final set of primary studies is 40[1]. The inclusion/exclusion criteria were also defined in an iterative way, evolving during the phases. The inclusion criteria were: papers from journal or conferences; english language; competency mapping; CBE assessment tools; CBE in computer science and engineering courses in higher education; and CBE curriculum models. The exclusion criteria were: secondary studies; non addressing CBE; non about engineering or computing; not in higher education; and technical documents.

3.2. Second stage - building the model

Primary studies were used as a basis for building this model. This process included the extraction of relevant data to characterize CBE interventions. In order to ensure the consistency of the extracted data, the extraction was carried out by one researcher and the results were checked by another researcher through regular meetings, where any discrepancies were resolved. As we read through the articles, we used an iterative and incremental approach to enter the information, progressively organizing a table that summarized the main characteristics of the interventions and the approaches applied. This process involved constant revisions to ensure that the data incorporated was relevant and appropriate to the model's objectives.

During the process of building the model, we expected certain dimensions to be identified in a large proportion of the studies analyzed. For this reason, some dimensions and their respective attributes were established in advance, based on expectations and the frequency of their presence in the studies reviewed. As an example, we can mention that all the articles present the analysis methods. Thus, this previously known attribute is part of one of the intervention's dimensions. Thus, we understand that in the dimension involving the presentation of the experiment (which we call Experimental Design), the method adopted is one of the attributes that needs to be presented.

When analyzing the studies, we observed a variation in the methods used to evaluate CBE interventions. For example, the article by [Rytikova and Boicu 2014] adopts an experimental method; that by [Vargas et al. 2019], a quasi-experiment; and that by [Gottipati and Shankararaman 2018], which adopts an ad-hoc strategy. Based on this methodological diversity, we established Experimental Design as a dimension in the model, with the specific method of each study defined as an attribute. This approach makes it possible to categorize and compare interventions according to the types of methods employed, facilitating the analysis of methodological practices in CBE.

While some dimensions were expected, others came to light as the studies were observed. For example, to characterize the studies analyzed, we noticed that there are studies with different focuses. Some are empirical studies [Félix-Herrán et al. 2019, García-Berdonés et al. 2016] and others focus on presenting assessment tools [Mäses et al. 2021, Rayón et al. 2014, Naeem et al. 2023]. Based on these observations, we defined the Characterization of the Intervention dimension, including attributes such as the specific Category of the study. In addition, some articles highlighted interventions based on recognized frameworks, such as Computing Curricula 2020 (CC2020) and Information Technology Curricula 2017 (IT2017), which led us to

[1]Articles used in this research: `https://doi.org/10.5281/zenodo.14878791`

include the attribute “Based on” to map the theoretical bases adopted as an attribute of the Characterization of the intervention dimension.

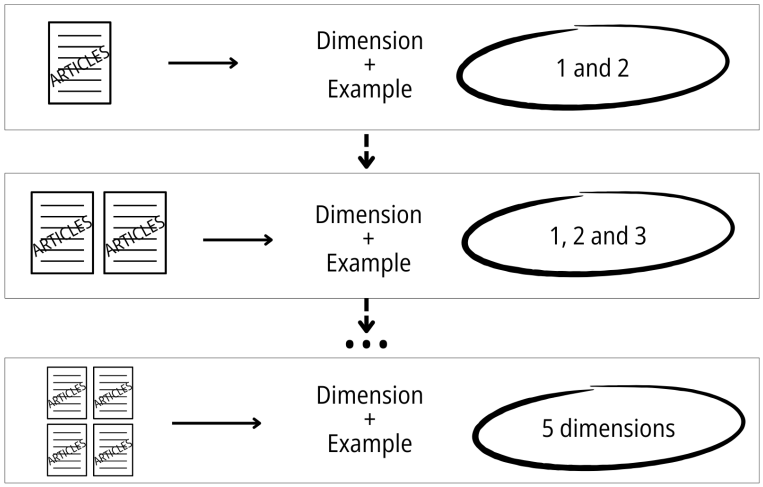

Figure 1. Process of building the reference model.

Overall, with each new primary study read and analyzed, attributes, dimensions, and examples were identified and refined, shaping the model through an iterative and incremental process. This approach allowed continuous adjustments, ensuring that the extracted data progressively improved the structure of the framework. Figure 1 illustrates this process, representing the progressive categorization of the model’s dimensions. The main rectangles in the figure represent each cycle of the process. Each main rectangle shows the primary studies, which are the *articles*, dimensions and examples found, and the number of dimensions found. Thus, for each cycle, from the top to the bottom, the figure indicates that new articles are considered (the left side). It also represents that dimensions are found based on examples extracted from the articles (center). Lastly, the number of dimensions found is increased (the right side) during the process. As a final outcome, the model comprises five key dimensions: Demographic studies, Characterization of the intervention, Target audience, Experimental design, and Data analysis.

4. Results

This section presents the model, highlighting its dimensions, attributes, and examples derived from the literature review, which is currently under publication. The model is structured around five dimensions: Demographic, Characterization of the intervention, Target audience, Experimental design, and Data analysis.

4.1. Demographic

In a study, it is important to understand the demographic composition of the studies. Data such as year of publication and evaluation context to clarify how these results might apply to different population groups, as well as mapping out what has been done in each time period, generating possible hypotheses within the field of research. We identified two attributes related to demographic information. Descriptions of these attributes, as well as entries examples, are presented in Table 1.

Table 1. Categorization of demographic information

Attributes	Description	Entry example
Year	Year of publication	2020, 2015
Evaluation context	What context does the evaluation address	Professional, Academic, N/A

4.2. Characterization of the intervention

Detailed information about the intervention helps replicating and analyzing the effect of contextual decisions on the investigation. For this information, was defined by the iterative and incremental process to use two attributes, given the context of our work. The attribute "Based on" identifies the number of studies based on existing frameworks or models. The attribute "Category" classifies the work into six types: (i) Practical Framework, (ii) Theoretical Framework, (iii) Survey, (iv) Practical Survey and (v) Validation Framework, or (vi) descriptive study with empirical data. The attributes of the category dimension are one of the most important elements of this study, as they address the types of studies carried out on the subject. The attributes are presented in Table 2.

Table 2. Characterization of the intervention

Attributes	Description	Entry example
Based on?	Was this article based on a CBE framework?	CC2020 or IT2017
Category	Classifies the works by the approach adopted	Practical Framework, Theoretical Framework, Survey, Practical Survey and Validation Framework, or Descriptive study with empirical data.

4.3. Target audience

The characterization of the target audience is important so that other researchers can analyze and replicate the actions carried out based on each type of audience, providing a better way to carry out CBE applications in higher education. We identified five attributes that were used to identify information about the Target audience dimension: Level, Previous Eexperience, Number of Participants, Quantity, and Duration. The descriptions of the attributes, as well as examples of entries found in the articles, are shown in Table 3.

4.4. Experimental design

In this dimension, we address four attributes, analyzing the instruments used in each study, with special attention to three main aspects: validity, evaluation perspective and analysis basis. Not all the articles analyzed provided clear information on the validity of the adopted instruments. However, some studies sought to ensure validity through content analysis, offering greater reliability to the results reported. The perspective adopted to carry out the evaluations was considered an important attribute in the analyzed studies. This perspective covered the point of view of the students, the teachers or both, highlighting different approaches to data collection and interpretation of the results.The approach used to analyze the results was classified into four main categories, which can be seen in Table 4.

Table 3. Target audience

Attributes	Description	Entry example
Level	Identify which level, undergraduate or postgraduate	graduation, postgraduate
Previous experience	Verification of previous experience with CBE interventions/implementations	Yes/No
Quantity	Number of participants in the intervention/implementation	310, 83
Location Brazil, USA, UEFS	Where was the study carried out?	Country or institution where the study occurred
Duration	Indicate the duration of the intervention	1 year, 1 semester, 15 weeks, 3 years

Table 4. Experimental design

Attributes	Description	Entry example
Instrument	If the article deals with evaluation, check if it has an evaluation tool.	Interviews, observations, questionnaires, tests or rubrics
Validity	Check and report whether the work has used any validation methods.	ANOVA, content and construct validation, Cronbach's alpha
Evaluation perspective	Evaluate whether the instrument was applied with a focus on student or teacher responses.	Student, teacher or both, directors
Basis of evaluation	How was the evaluation carried out? Self-report, behavior, test, mixed	Self-reporting, behavior analysis, and both

4.5. Data analysis

Information such as the type of study and the method used is important for understanding the adopted approach by each piece of research and its contribution to the field. This information makes it possible to identify whether the study is a case study, experimental or quasi-experimental, as well as clarifying the methods used, such as qualitative, quantitative or mixed analyses. This characterization is fundamental for assessing the robustness and applicability of the results presented.

Table 5. Data analysis

Attributes	Description	Entry example
Type of study	Type of study reported by the articles	qualitative, quantitative, mixed, N/A
Study method	Method used in the research approach	quasi-experiment, case study, N/A

The application of the model revealed relevant patterns in CBE research, highlighting the predominance of qualitative studies and the emphasis on the perception of students and teachers. In addition, a lack of more robust quantitative and experimental approaches was identified. These insights highlight the usefulness of the model in organizing research and identifying gaps, promoting greater clarity in the analysis and comparison of studies in the area.

5. Discussion

The main objective of this work is to propose a reference model to support research in the area of CBE in computing and engineering. Based on the analysis of primary studies, the model was developed to structure and standardize the presentation of interventions and experiences, making it easier to organize information, compare studies and assess the quality of research. The proposed model is made up of five main dimensions: Demographics, Intervention Characterization, Target Audience, Experimental Design and Data Analysis. These dimensions structure CBE research in a clear and organized way.

The model's proposal impacts research in the area from three main perspectives. The first concerns the formulation of new studies. As the literature on CBE in computing and engineering is still limited, many researchers may find it difficult to structure their studies. The model helps in this process by providing a reference structure for categorizing interventions, defining basic frameworks and choosing appropriate categories. For example, when developing a study on the implementation of CBE in an engineering course, the researcher can draw on the proposed dimensions to define the methodological design and evaluation criteria.

The second perspective is related to the presentation of work. The template acts as a guide for the effective communication of results, ensuring that all relevant elements are described in a systematic way. In this way, researchers who wish to publish articles or reports can use the template to structure their research, including essential information such as the target audience of the intervention and the method of data analysis.

The third perspective is evaluating the quality of the work. The model can be used as a tool for critical analysis when reading studies, allowing researchers to assess whether all the necessary information is present and properly organized. This is particularly important in secondary studies, as systematic reviews or systematic mapping studies, where the selection and extraction of data from primary studies follows strict criteria. By using the model, it is possible to ensure that the articles analyzed contain clear and standardized descriptions, allowing for better comparison and extraction of information.

6. Conclusions

The proposed model benefits both researchers and educators. For researchers, it standardizes the analysis of CBE studies, facilitating comparisons and identifying gaps in the literature. For educators, it allows them to understand and adapt evidence-based methodologies, supporting the implementation of CBE in engineering and computing. Researchers and practitioners can adopt the model as a guideline to plan and implement their CBE teaching approaches. This supports more structured and effective analysis. The second aspect refers to the detection of relevant data for in works on CBE, supporting secondary studies, such as systematic reviews or systematic mapping studies.

The model synthesizes key information extracted from primary studies identified from a systematic selection approach. This offers a solid basis for the analysis and comparison of practices and approaches adopted in different contexts of higher education in computing and engineering.

The model's structure was developed iteratively, incorporating dimensions and attributes extracted from primary studies selected with methodological rigor. Despite this,

one may have to state that the limitation of the work regards the model validation. Due to the constraint space, this paper focuses on the presentation of the model. Validation may involves applying the model to systematic reviews and secondary studies to verify the comprehensiveness and representativeness of the attributes, for example. Another point to be considered is that the model includes a comprehensive set of elements. The need to include all items depends on the context and purpose of the research. Therefore, its use is mainly recommended for studies that seek to structure and analyze CBE interventions in higher education, and it can be adapted as new evidence and needs arise.

The model can be considered robust, as it is based on evidence provided by the literature review, which offers valuable information and indicators for evaluating its effectiveness. However, a threat to the validity of this study is the fact that the review has not yet been published and is currently in the submission phase. The dimensions identified have been systematically derived from the literature, ensuring that the model is comprehensive and adequate to address key aspects of competence-based teaching. By drawing on the conclusions of the review, the model is theoretically grounded and applicable in practice, providing a solid basis for future research and implementation. The proposed model helps to structure and standardize studies on CBE, allowing it to be applied to the organization of research, systematic reviews and analysis of methodological quality. It facilitates the replication and comparison of studies, identifying patterns and gaps in the literature, contributing to greater rigor in research on CBE.

As future work, we propose the adoption of the model for secondary studies. In fact, we are carrying out a systematic review on CBE adopting the model as a guideline for extracting data from primary studies. In addition, the model might evolve as more data is extracted from other studies. New dimensions, attributes and examples can be identified, allowing for continuous improvement and expansion of the model, building on the proposition of new interventions and approaches in the field of CBE teaching.

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